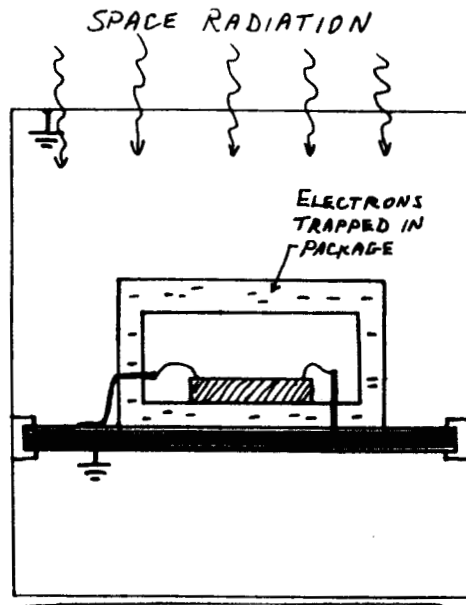


**Electrostatic Discharge Induced in Packaging  
by Space Radiation**

**A. R. Frederickson and Tien T. Nguyen**

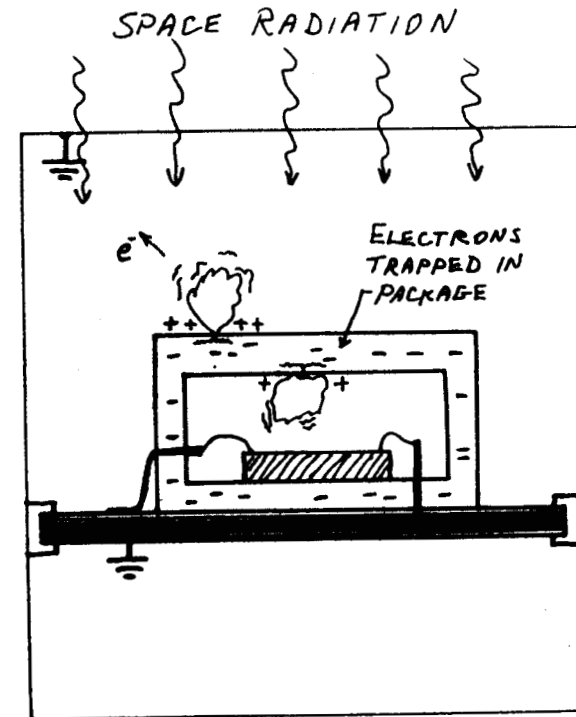
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Radiation belts around planets have sufficient high-energy electron flux to penetrate spacecraft skins and statically charge insulators inside the electronic boxes. For example, geosynchronous-orbit Earth spacecraft require 100 mils aluminum shielding to sufficiently attenuate the fast electron flux.

Electrons are stopped and accumulate slowly in the insulated materials to produce strong electric fields. Typically the field strength achieves a threshold for occasional spontaneous discharge in the insulating material. The field strength remains high yet pulsing is infrequent.

Charge can leak off if the insulator is sufficiently leaky. The conductivity of insulators is usually controlled by mobile ions such as H and OH in ground service. In space the mobile ions are eventually out-gassed. The resistivity of several insulators is known to increase over three decades after exposure to vacuum for several months. Insulators in space were seen to pulse more frequently as they aged.



A discharge tree spontaneously forms in the insulator and issues a burst of gas into the vacuum. The electric field in the vacuum further ionizes the gas which forms a high resistance ( $>100$  ohms) path between the insulator surface and other surfaces in the region. The high-voltage on the surface of the insulator is discharged to the conductors that connect with the gas. Since the surface may have been charged to many kilovolts the discharge currents can be many amperes.

**Predict Event Rate**

**Estimate Peak Discharge Current**

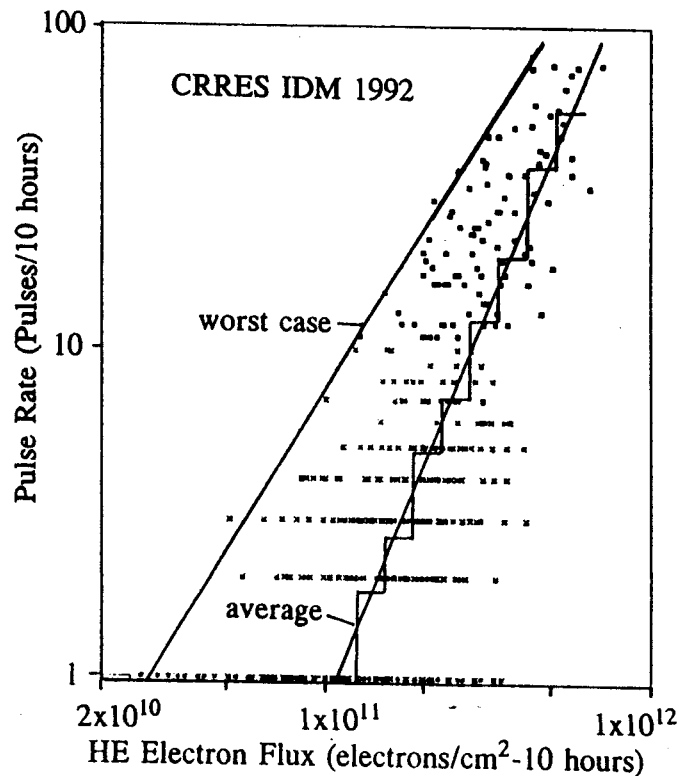
**Estimate Pulse Width**

**Discuss Gas Connections**

**Develop Test Procedures**

**Develop Fixes**

The pulse rate has been measured in space for a number of materials. Fourteen months of data have been divided into many ten hour bins. The number of pulses in each ten hour bin is plotted as a function of the electron fluence during that ten hours. Thus if one knows the flux of electrons, one may estimate the rate of occurrence of pulses. This data reflects FR4 circuit board material in the main, but includes other materials. Packaging material has not been tested.

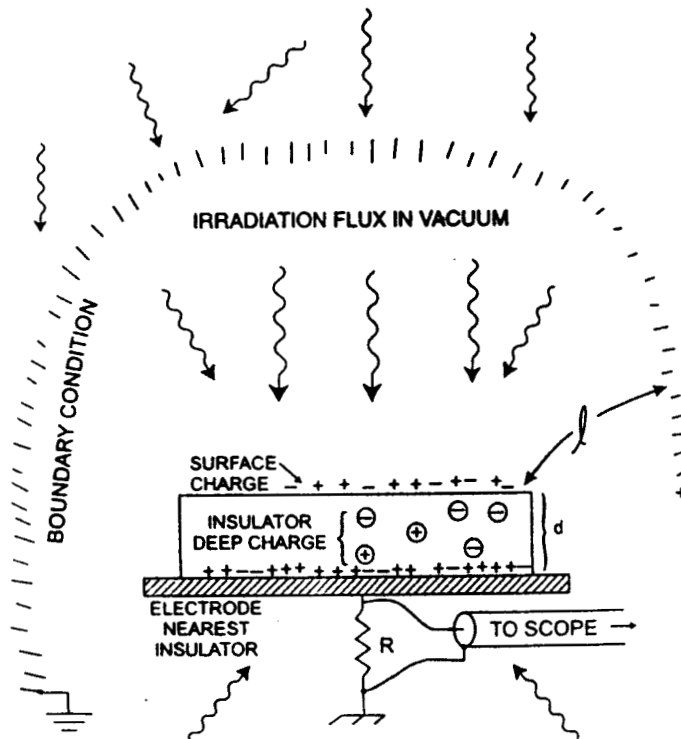


## RADIATION-CHARGING OF INSULATOR MATERIAL

If one considers an entire spacecraft, the boundary condition is the ambient space plasma "ground" voltage. Both the spacecraft body and its surface insulators are charged relative to plasma "ground."

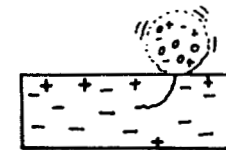
Or, if one considers internal parts of the spacecraft, the boundary condition might be the conductive skin of the spacecraft, and the insulator is one of the internal materials. High energy electrons pass through spacecraft skins.

When the insulator spontaneously discharges it emits a burst of charge, plasma, and neutral gas into the vacuum. The electric field in the vacuum drives a pulse of current in the plasma. A portion of the pulsed displacement current is monitored on the oscilloscope.

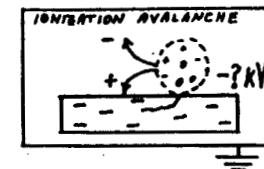


## PHYSICS

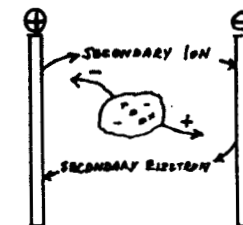
Insulating material under E-field stress spontaneously creates burst of plasma, and forms a channel in or on material.



In vacuum, the plasma avalanches (Paschen discharge) when surfaces are at high voltage thereby lowering surface potentials.

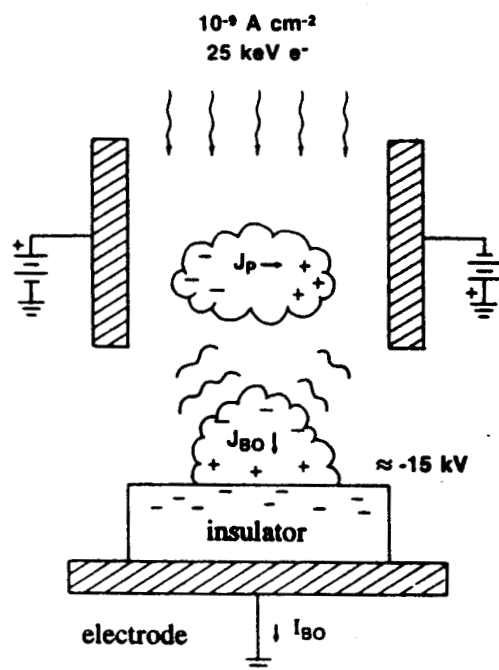


Neutral + Plasma gas may be dense or sparse. Further carriers are generated at surfaces and may form permanent arc with batteries. Arc ends when vacuum E-fields are small.



## INVESTIGATION OF PULSED CURRENTS

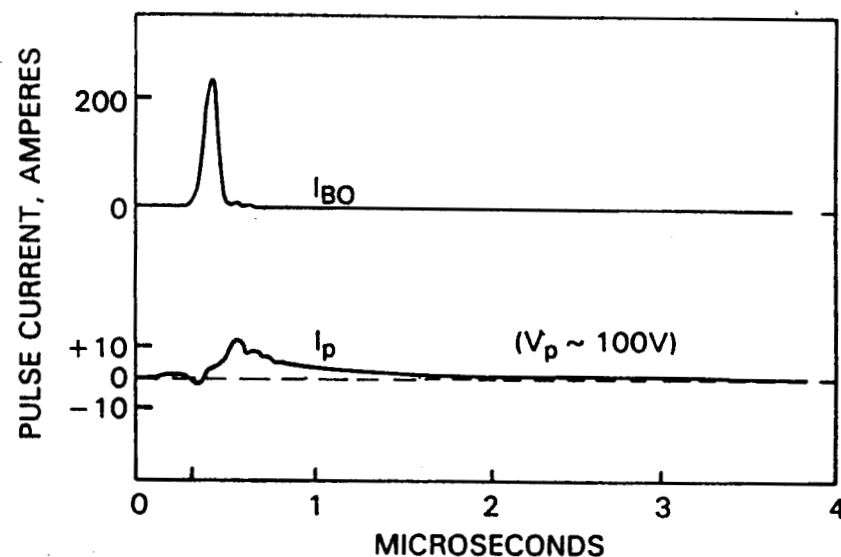
A burst of plasma and gas is spontaneously emitted from the charged insulator. If the insulator surface voltage is far from ground, a pulse of current in the plasma will rapidly ground it. The plasma conducts current amongst other electrodes as well.



WE SEPARATE CURRENTS INTO TWO COMPONENTS:  
PLASMA,  $J_p$ , and BLOWOFF,  $J_{bo}$ .  
BOTH ARE CONDUCTED BY PLASMA.

BATTERIES DRIVE  $J_p$ , AND SURFACE VOLTAGE  
DRIVES  $J_{bo}$ .

## MEASUREMENT OF EMP CURRENTS

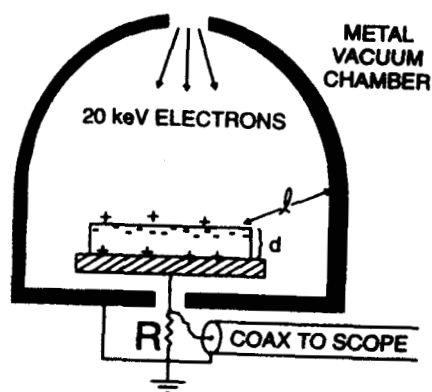
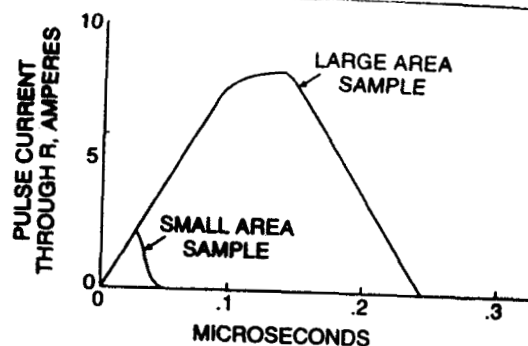


A TYPICAL PAIR OF SIMULTANEOUS CURRENT PULSES FROM ONE DISCHARGE EVENT. HUNDREDS OF PAIRS WERE RECORDED.  $I_{bo}$  BARELY REGISTERS ON THE  $I_p$  TRACE, AS EXPECTED.  $I_p$  CONTINUES LONG AFTER THE BLOWOFF CURRENT HAS DISCHARGED THE SURFACE OF THE SAMPLE. PLASMA ELECTRODE BIAS IS 100 VOLTS.

This proves that the plasma and gas remain long after the insulator surface is discharged. The plasma is able to conduct current amongst other charged surfaces. Therefore, the details of the gas/plasma phase may be critical for understanding EMP pulses induced in spacecraft circuits.

## EMP PRODUCED INSIDE ELECTRONIC BOXES ON A SPACECRAFT

Penetrating high energy electrons charge the insulators on wires, circuit boards, integrated circuits, connectors, capacitors, etc. A spontaneous discharge produces a pulse of plasma and current which couple to nearby circuits. The plasma cloud is shown in the figure. As the cloud expands, we see three kinds of signals on the circuits. The arrows indicate direction of positive current.



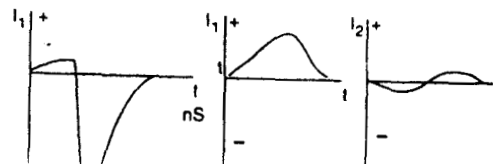
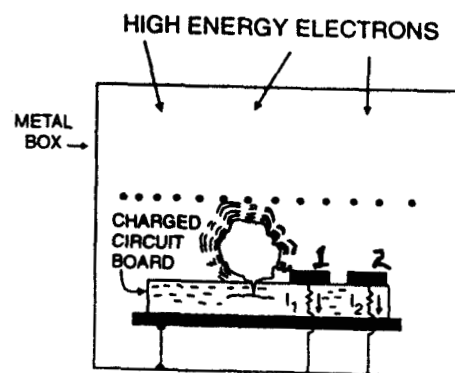
The discharge pulses are simple and consistent when the test geometry is simple. In a vacuum chamber with conductive walls the discharge usually proceeds from the sample surface across the vacuum to the walls. In that case there is positive current through  $R$  as the positive image charge in the sample electrode passes through  $R$ , to the vacuum walls, and through the vacuum plasma onto the front surface of the sample.

The current pulse has a slow rate (slope) determined by the sample material, by the surface electric field, and by the vacuum spacing. Changing the size of the sample only changes the duration of the pulse. The duration is determined by the amount of charge that is necessary to discharge the surface potential.

1. FIRST GRAPH. The electrode (#1) nearest the discharge site "sees" electrons leaving the charged insulator and moving towards the box walls early in the EMP. But when the plasma cloud expands to "connect" to the electrode, current  $I_1$  rapidly turns negative with a large slew rate. Most of the surface voltage of the insulator is discharged to the circuit  $I_1$ .

2. SECOND GRAPH. If the cloud does not connect to electrode #1, then the current  $I_1$  remains positive. The total charge in  $I_1$  is simply the positive image charge that was established in electrode #1 by the nearby trapped electrons in the insulator. The trapped electrons were introduced by the high energy electron irradiation.

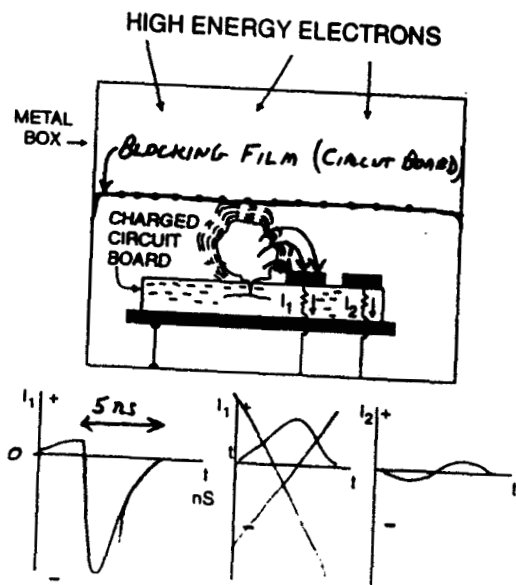
3. THIRD GRAPH. Electrodes far from the discharge region, such as electrode #2, do not contain image charge relative to the portion of the board that is discharging. The plasma cloud may not connect to electrode #2. However, as the plasma carries charge across the vacuum space, a bipolar current is induced in electrode #2 by that charge flow. The integral under  $I_2$  is nearly zero.



THE WORST CASE IS ACHIEVED WHEN THE PLASMA CLOUD CONNECTS TO THE SENSITIVE CIRCUIT, AND DOES NOT CONNECT TO OTHER CIRCUITS. THEN THE ENTIRE INSULATOR SURFACE CHARGE PASSES INTO THE SENSITIVE CIRCUIT.

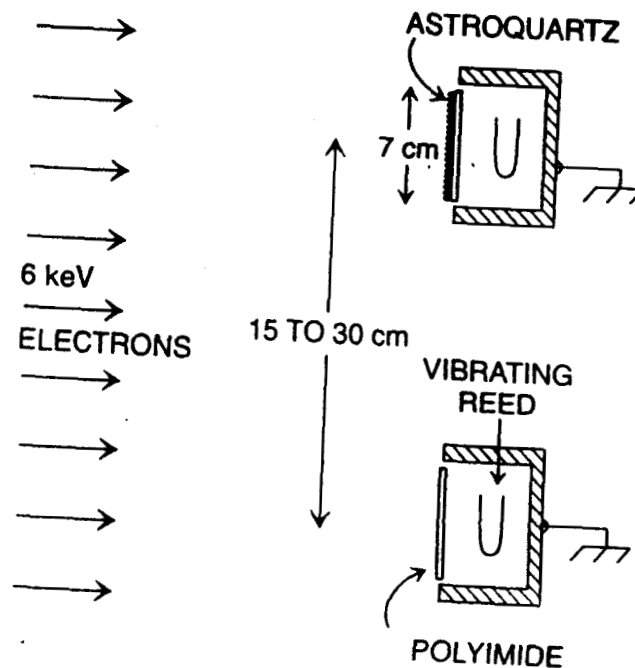
In the previous figure, some of the plasma current passed to the walls of the electronic box. In this figure a poorly conducting film is placed above the discharging circuitboard. The film blocks the passage of the plasma current to the box walls. All of the discharge current will then connect to  $I_1$  and produce the largest possible EMP current pulse in the circuit.

BRIEF EXPERIMENTS INDICATE THAT THESE PULSES HAVE SLEW RATES EXCEEDING  $10^{10}$  A/sec, AND PEAK VOLTAGES ON 50 OHM CIRCUITS EXCEEDING 2 kV.



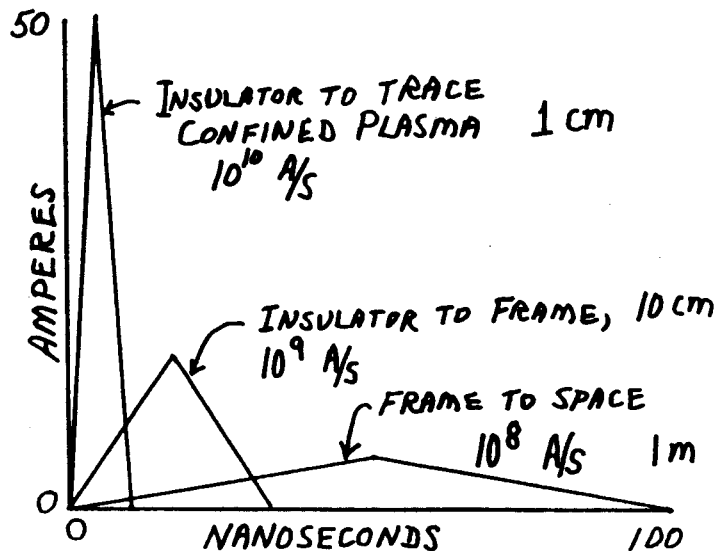
## HOW FAR AWAY CAN THE GAS/PLASMA BURST DISCHARGE ANOTHER SURFACE ?

The potentials of two floating samples were monitored by vibrating reed electrometers while being irradiated by 6 keV electrons. Only the Astroquartz glass fabric produces pulses which discharge its potential in such an irradiation. During several hours of 6 keV irradiation the polyimide alone experiences no discharges. Chart recorders continuously monitor the potentials for the occurrence of pulses on each sample. During two hours of side by side irradiation, the Astroquartz produced over 1000 pulses, but the polyimide produced only ten pulses. Each of the ten pulses on the polyimide potential occurred simultaneously with pulses on the astroquartz. It is presumed that plasma pulses from the astroquartz caused all ten of the polyimide discharges. Thus, approximately one percent of the plasma/gas bursts spread as far as 20 cm to initiate a secondary discharge pulse on another surface.



## PULSE SCALING LAW

$$\int_0^{\infty} I(t) dt = Q_0 \text{ (moving holes)}$$



Electronic packaging is usually in a geometry where the plasma is confined and connection to conductors will occur with a relatively dense plasma with low resistance. This produces the highest slew rate,  $1E10 \text{ A/sec}$ .

The charge that will flow through the plasma to the (grounded) conductor is determined by the capacitance of the high-voltage surface to ground, and its voltage. Typical voltages could be as high as 10 kV, and capacitance is of the order of 10 pF.  $Q = CV = 1E-7 \text{ coulombs}$ .

$$\Delta t = \sqrt{4Q/S}$$

$$= \sqrt{4E^{-7}/10^{10}} = 6 \text{ nsec}$$

$$I_{\text{peak}} = \frac{S \Delta t}{2}$$

$$= 30 \text{ AMPERES}$$

This is the expected maximum value for peak current, and assumes that the image charges will redistribute through the plasma and perfect conductors otherwise.

In reality, the nearby conductors will have some impedance to ground and thus some of the initial 10 kV will be impressed across this impedance. It helps to know the impedance of the plasma in order to know the voltages impressed on other circuits. The 30 amperes flows when the voltage has dropped to 5 kV, so the plasma impedance at this instant of time is approximately 200 ohms.

Further voltage division will occur through capacitive dividers. It is possible that some sensitive nodes will be briefly raised to the order of 100 to 1000 volts. Much depends on the initial distribution of image charge and on the spatial evolution of gas.



## **TEST PROCEDURES**

**Measure insulator charge storage  
using e-beam**

**Measure pulses generated by dummy  
packages**

**Apply simulated pulses to circuits**

## **FIXES**

**Develop Leaky Insulators**

**Coat Surfaces with Leaky Paint  
(inside package too)**

**Block plasma connection to good  
conductors.**

**Put gas, not vacuum inside packages  
(other problems occur)**

**Shield from Space Radiation**

**Use very thin package insulation.**

**Put series resistance in circuits.**